Assessment of rock glaciers, water storage, and permafrost distribution in Guokalariju, Tibetan Plateau

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Abstract. Rock glaciers are important hydrological reserves in arid and semi-arid regions. Rock glaciers', and their activity statesstatus can indicate the existence of permafrost. To help explore further the development mechanismsmechanism of rock glaciers in the semi-arid and humid transition regionsregion, this paper provides a detailed rock glacier inventory of the Guokalariju (GKLRJ) area ofin the Tibetan Plateau (TP) using aby manual visual interpretation offor the Google Earth Pro remote sensing imagery. We alsoimages. Meanwhile, we estimated the water volume equivalent (WVEQ) and thepermafrost distribution of permafrost probabilities in the probability of GKLRJ for the first time. Approximately 5,053About 5053 rock glaciers were identified, covering a total area of ~about 428.71 km^2. Rock glaciers arewere unevenly distributed within the three sub-regions R1, R2 and R3 from east to west, with 80% of them concentrated in R2, where climatic and topographic conditions are most favorablefavourable. Limited by topographic conditionsthe north-south trend of the mountains, rock glaciers arewere more commonly distributed onin the west-facing aspectsaspect (NW and W). When other conditions arewere met, increases in the increase of precipitation arewas conducive to rock glaciers forming at distributing to lower altitudes. Indeed, the , their lower limit of rock glaciers' the mean distribution altitude decreased eastward,to the eastern region with increasing precipitation. Estimates of the water storage capacity of rock glaciers obtained by applying different methods variedvary considerably, but all showed the potential hydrological value of rock glaciers. The maximum possible water storage in these rock glaciers was 6.82 km^3, or ~which was approximately 56% of the local clean ice glacier storage. In R1, where the climate is the driest, theThe water storage capacity of rock glaciers was estimated to can be up to twice as large as that of the sub-region's clean ice glaciers. reserved in R1, where the climate was the driest. Permafrost is widespread above ~ 4,476about 4476 m above sea level (asl). Our a.s.l., and the results showed that the regression model, based on the rock glacier inventory, can consistently predict the possible range of modern permafrost. These in the recent period. In addition, the results may also have some reference value forin regional water resourceresources management, disaster prevention, and sustainable development strategiesstrategy formulation.

1 Introduction

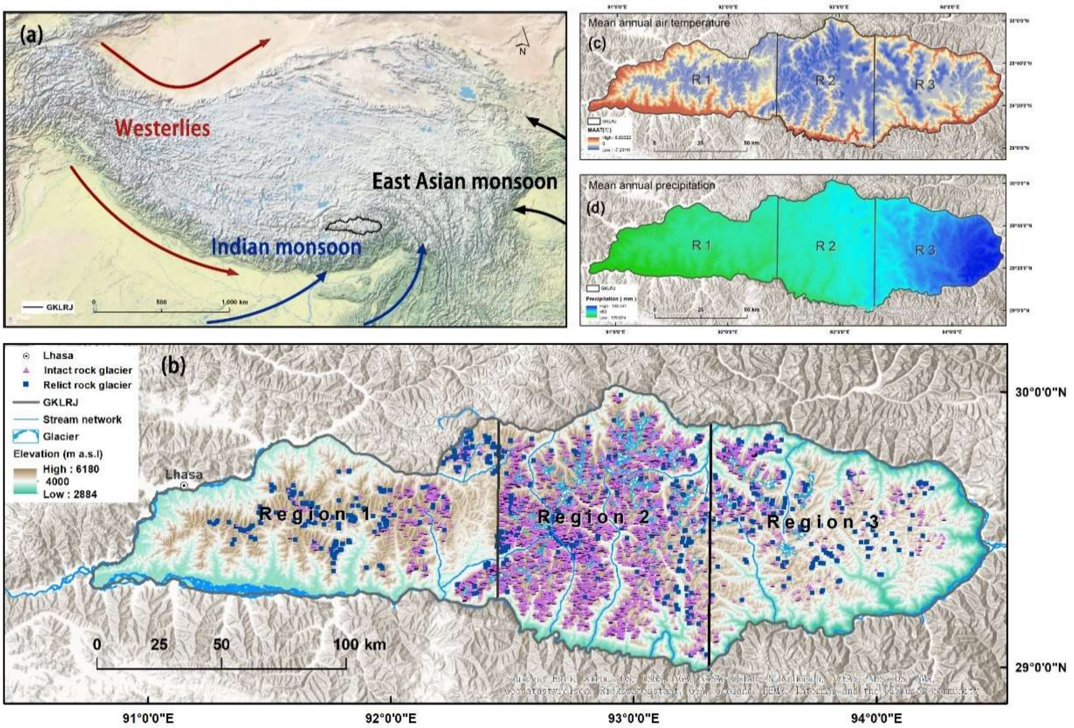
Rock glaciers are periglacial landforms often observed above the timberline in the alpine mountains. They are and formed by rocks and ice that move down athe slope, driven by gravity (French, 2007; RGIK, 2021). As striking features of viscous flow in perennially frozen materials, they can reflect permafrost conditions in mountainous areas. Their lowest altitudeselevations are often considered to represent the lower limit of discontinuous regional permafrost occurrence (Giardino and Vitek, 1988; Barsch, 1992, 1996; Barsch, 1996; Kääb *et al.*, 1997; Schmid *et al.*, 2015; Selley *et al.*, 2018; Baral *et al.*, 2019; Hassan *et al.*, 2021);), and their statesactivity state (intact or relict) can be used in the Permafrost Zonation Index (PZI) models to predict the probability of permafrost occurrence where field observation data are scarce (Cao *et al.*, 2021; Boeckli *et al.*, 2012a). The large-scale distribution of active rock glaciers is influenced by the complex interaction of climaticclimate and topographic factors (Schrott, 1996; Millar and Westfall, 2008; Pandey, 2019). GlobalIn the context of global climate change may affect, the stability of rock glaciers and permafrost may also be affected, thus impactingaffecting slope stability, vegetation coverage, runoff patterns, and water quality, with possible consequences foron periodic landslides, debris flows, floods, and other geological disasters (Barsch, 1996; Schoeneich *et al.*, 2015; Blöthe *et al.*,2019; Hassan *et al.*, 2021). ExploringTherefore, exploring their spatial distribution and evolution is therefore significant for paleoclimaticpaleoclimate modeling, disaster risk assessment, and infrastructure maintenance (Arenson and Jakob, 2010; Colucci *et al.*, 2016; Selley *et al.*, 2018; Alcalá-Reygosa, 2019). Furthermore, the slow thawing process through heat diffusion with latent heat exchange at depth, combined with the cooling effect of the ventilated coarse blocks at the surface of rock glaciers, make themit a largely inert hydrological reserve in high mountain systems (Bolch and Marchenko, 2009; Berthling, 2011; Bonnaventure and Lamoureux, 2013; Millar and Westfall, 2013). The), their presence and abundance of rock glaciers can therefore affect the quantitiesamount and properties of runoff from high mountain watersheds over extended time periods (Bosson and Lambiel, 2016; Jones *et al.*, 2019b).

The Tibetan Plateau (TP) is among the key high-altitude areas of periglacial landform worldwide, and is a region highly sensitive toarea for climate change (Cui *et al.*, 2019; Yao *et al.*, 2019). Detailed rock glacier inventories of rock glaciers have been previously been constructed forin the regions of the Gangdise Mountains (Zhang *et al.*, 2022), the Daxue MountainsShan (Ran and Liu, 2018), the Nyainqêntanglha Range (Reinosch *et al.*, 2021), and the Nepalese Himalaya (Jones *et al.*, 2018b). The Yarlung Zangbo River Basin (YZRB)basin is one of the regions with the highest concentrationsconcentration of modern glaciers on the TP; it is experiencing and the mostfastest rapid geomorphic evolution on Earththe earth today (Ji *et al.*, 1999; Korup and Montgomery, 2008; Yu *et al.*, 2011; Long *et al.*, 2022). Although Guo (2019) has characterized the spatial distribution of rock glaciers in the YZRB usingYarlung Zangbo River watershed by manual visual interpretation, there remainsis still a lack of anya systematic and detailed rock glacier inventory, and the regional occurrence characteristics and indicative environmental significance of these rock glaciers are still unclear. Even thoughMeanwhile, in spite that the ground-penetrating radar (GPR), seismic refraction tomography (SRT), electrical resistivity tomography (ERT)), and other geophysical techniques are widely used today and can provide new insights into understanding the ice volumesvolume content of rock glaciers and permafrost (Janke *et al.*, 2015; Emmert and Kneisel, 2017; Bolch *et al.*, 2019; Buckel *et al.*, 2021; Halla *et al.*, 2021; Mathys *et al.*, 2022), it remains problematicis still difficult to apply such methods to large-scale field-based research on thein TP. The permafrost distribution of permafrost and the hydrological contributions made by contribution of rock glaciers onin the TP need more research.

To address this, our study aims to: (i) compile a more comprehensive and systematic inventory ofsystematical rock glaciers in the GLKRJ;, (ii) explore the regional occurrence characteristics and indicative environmental significance of these rock glaciers;, (iii) assess the regional hydrological significance of rock glaciers and clean ice glaciers; and, (iv) model the permafrost probability distribution of the GLKRJ's permafrost probabilities.

2 Study area

Guokalariju (GKLRJ) is located between 92.916°N-93.276°N and 29.287°E-29.438°E in the southeast TP, adjacent to the Himalayas in the south and Nyainqêntanglha Range in the north (see Fig.1). It is the eastern extension of the Gangdise Mountains as well as the watershed of the Yarlung Zangbo River and its tributary Niyang-Lhasa River, belongs to the high mountain plateau-lake basin-wide valley area in the middle and upper reaches of the Yarlung Zangbo River and Nujiang River (Xiang *et al.*, 2013).



Meanwhile, as the transition belt between the plateau semi-arid and humid region (Zheng *et al.*,2010), it is an important window to study the periglacial geomorphology.

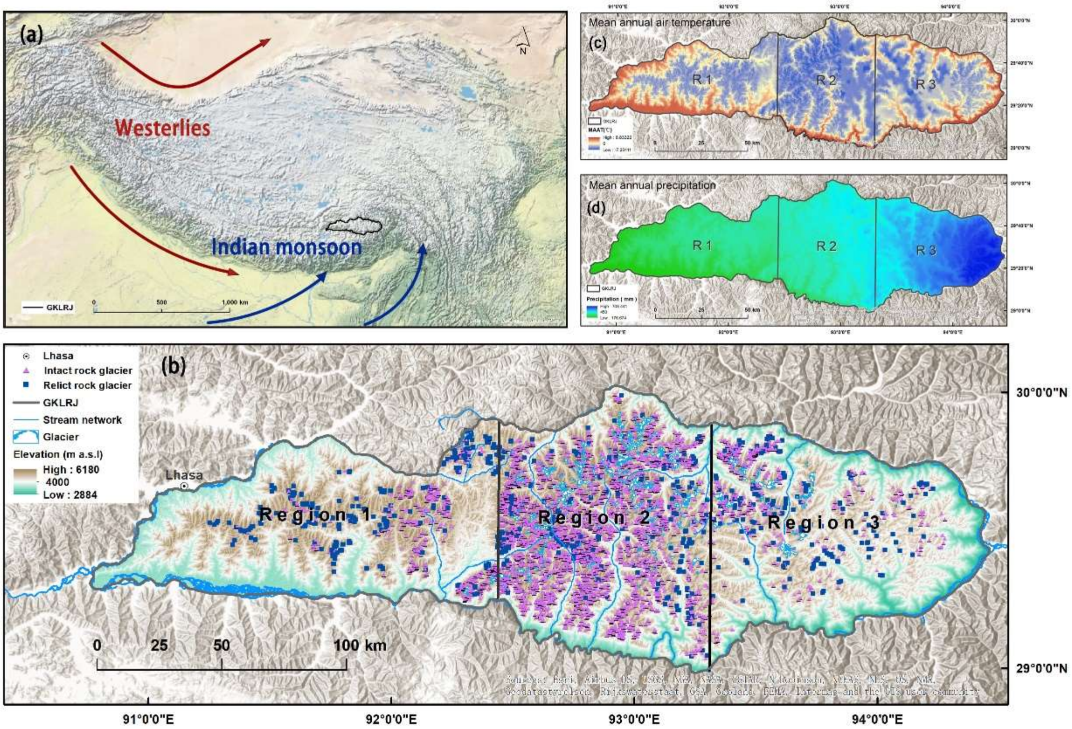


Figure 1: (a) The location of the GKLRJ on~~in~~ the TP;~~,~~ (b) The three sub-regions and the spatial distribution~~distributions~~ of streams. Rock glaciers are categorized as purple (intact rock glaciers), blue (relict rock glaciers), and glaciers are shown in blue and white;~~.~~ (c) Mean annual air temperature map for the~~in~~ GKLRJ (Du and Yi, 2019);~~),~~ (d) Mean annual precipitation map for the~~in~~ GKLRJ (Du and Yi, 2019). Maps were created using ArcGIS® software by Esri.

The GKLRJ region is located between 92.916°N-93.276°N and 29.287°E-29.438°E, on the southeastern TP, adjacent to the Himalayas to the south and the Nyainqêntanglha Range to the north (see Fig.1). It forms the eastern extension of the Gangdise Mountains as well as the watershed of the Yarlung Zangbo River and its tributary, the Niyang-Lhasa River, and belongs to the high mountain plateau-lake basin-wide valley area of the middle and upper reaches of the Yarlung Zangbo and Nujiang rivers (Xiang *et al.*, 2013). As the GKLRJ is located in the transition belt between the TP's semi-arid and humid regions (Zheng *et al*., 2010), it is seminal to the study of periglacial geomorphology.

Tectonically, the GKLRJ~~it~~ is located in the eastern part of the Ladakh-~~-~~Kailas-Xiachayu magmatic arc ~~belt~~ of the Gangdise-Himalayan collisional orogen; from the Late Paleozoic to the Mesozoic, it ~~, and~~ has experienced~~undergone~~ the same evolutionary tectonic processes as~~evolution process of the development of~~ the Gangdise-Himalayan archipelagic arc-basin systems, *i.e.*, back-arc spreading, arc-arc collision and arc-continental collision ~~from the Late Paleozoic to the Mesozoic~~ (Pan *et al.*, 2013). The GKLRJ's main rock types include Late Cretaceous quartz monzonite, Eocene monzonite~~,~~ and Eocene biotite granite. Mainly dominated by the Indian Summer~~summer~~ Monsoon (ISM), the middle and western parts of the GKLRJ belong to the TP's temperate, semi-arid zone~~region of the plateau~~, while the eastern part belongs to plateau's~~the~~ temperate humid region (Zheng *et al.*, 2010). The mean annual air temperature (MAAT) is -7.2 ~~~~~ 8.8ºC ~~8℃~~(Du and Yi, 2019), and the mean annual ground temperature (MAGT) is -3.2 ~~℃~~~ -4.3ºC~~3℃~~ (Ran *et al.*, 2020). The mean annual precipitation (MAP) is 177-708 mm, decreasing from ~~the~~ east to ~~the~~ west across~~of~~ the study area (Du and Yi, 2019).

Table 1: Topo-climatic~~climate~~ data for the~~of~~ GKLRJ and its three sub-regions.

Region	MAAT (ºC℃)	MAGT (ºC℃)	MAP (mm)	Altitude (m asl)a.s.l.)	Mean glacier ELA of glaciers (m asl)a.s.l.)
All	0.69	0.53	469	4,6234623	5,4315431
R1	1.78	1.65	385	4,5894589	5,4845484
R2	-0.63	-0.06	489	4,8934893	5,4625462
R3	0.91	0.01	534	4,3984398	5,2925292

MAGT: mean annual ground temperature
MAAT: mean annual air temperature
MAP: mean annual precipitation

We divided the GKLRJ into three sub-regions: R1(east);), R2 (central);(middle), and R3(west). These divisions were geospatially) based on the geographical spatial pattern (see Fig.1b),1(b)), where R1 and R2 are bounded by the eastern marginalmargin rift valley of the Oiga Basin, andbasin, R2 and R3 are bounded by Niang River, a tributary of the Niyang River. Each sub-region displayshas unique characteristics in terms of its topography and climate (see Table .1). The whole of R1 is a semi-arid region, and the terrain is more complex here. The western side of R1 is composed of a deep alpine valley landscape formed by glacial-fluvial erosion cutting through the undulating terrain, while the eastern side is a basin formed by late paleoglacialpalaeoglacial erosion and fluvial erosion cutting through the less undulating mountainous hills with relatively gentle tops (Wu *et al*., 2010). R2 is a semi-arid and semi-humid transition zone where the dividing line is located in its northeastern part;, and the mean altitudeaverage elevation here is higher than in the other regions. The main peaks of glacier-carved mountains occur mostly above 5,5005500 m asl.a.s.l. in altitude. R3 is located in a semi-humid zone where precipitation is more abundant and the terrain is on average ~down about 500 m lower than that offrom R2.

3 Material and methods

3.1 Rock glacier inventory, classification, and database

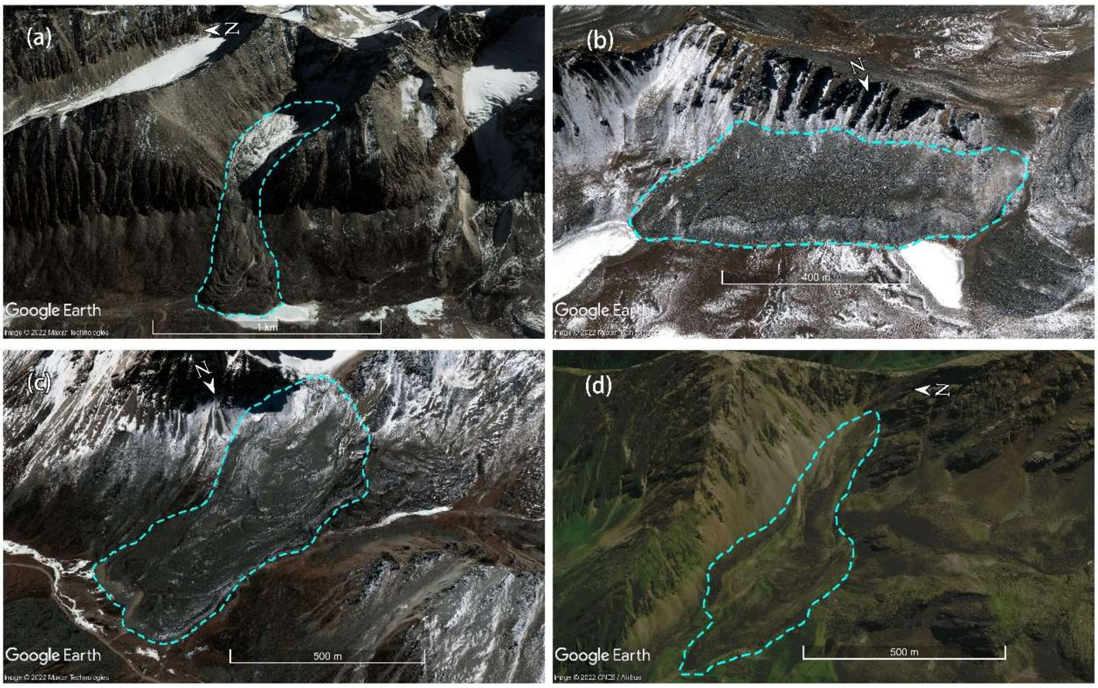


Figure 2: Example images of different types of rock glaciers in GKLRJ. (a) Intact debris-derived rock glacier, (b) Intact talus-derived rock glacier, (c) Relict debris-derived rock glacier, (d) Relict talus-derived rock glacier. Image ©Google Earth.

We used high-resolution ©Google Earth Pro remote sensing images from February 2009 to December 2020 to manually and visually interpretmanual visual interpretation and compile athe inventory of rock glaciers inventory for thein GKLRJ (Selley *et al.*, 2018; Magori *et al.,* 2020; Hassan *et al.,* 2021). The identified rock glaciers were delineated from the rooting zone to the foot of the front slope in Google Earth Pro following the method used in previous studies (Scotti *et al.*, 2013; Jones *et al.*, 2021). The), and the central point, length (parallel to flow) and width (vertical to flow) were also digitized in Google Earth Pro. We re-examined and adjusted the outlines of rock glaciers after the RGI_PCv2.0 (RGIK, 2022) update to ensure that they compliedcomply with the latest guidelines. Due to the lack of accurate field observationsobservation and related data on rock glacier dynamics, theirthe activity statesstatuses were determined according to the front slope, vegetation coverage, surface flow structures, rock glacier body, and other geomorphic indicators. We divided rock glaciers into two types (intact/relict) according to the method used byof Scotti *et al.* (2013). The active and inactive types were co-are designated together as 'intact rock glaciers' in this study (Haeberli, 1985; Pandey, 2019; Jones *et al.*, 2021). The intact rock glaciers usually have steep front slopes and lateral edges, an absence of vegetation cover, and apparent flow structures, such as ridges and furrows. The relict rock glaciers have relatively gentle frontal slopes, poorly defined lateral margins, a subdued topography, and less prominent flow structures (Scotti *et al.*, 2013; Baral *et al.*, 2019). Based on the sourcessource of the sedimentary material, we divided these rock glaciers into four types: (A) intact debris-derived rock glaciers;glacier, (B) intact talus-derived rock glaciers;glacier, (C) relict debris-derived rock glaciers; andglacier, (D) relict talus-derived rock glaciersglacier (see Fig. 2). TheAmong them, the talus-derived rock glaciers are mostly located at the bottom of the talus slopes, and principally transportslope, mainly transporting frost-shattered rock fragments derived from adjacent rock walls that have fallen under the force of gravity. The, while the debris-derived rock glaciers are related to perennially frozen morainic material from older glacialglacier advances that mostly between thefrom Holocene and theto Little Ice Age (LIA), and, mainly transporttransporting reworked glacial debris (till) (Barsch, 1996; Lilleøren and Etzelmüller, 2011; Scotti *et al.*, 2013).

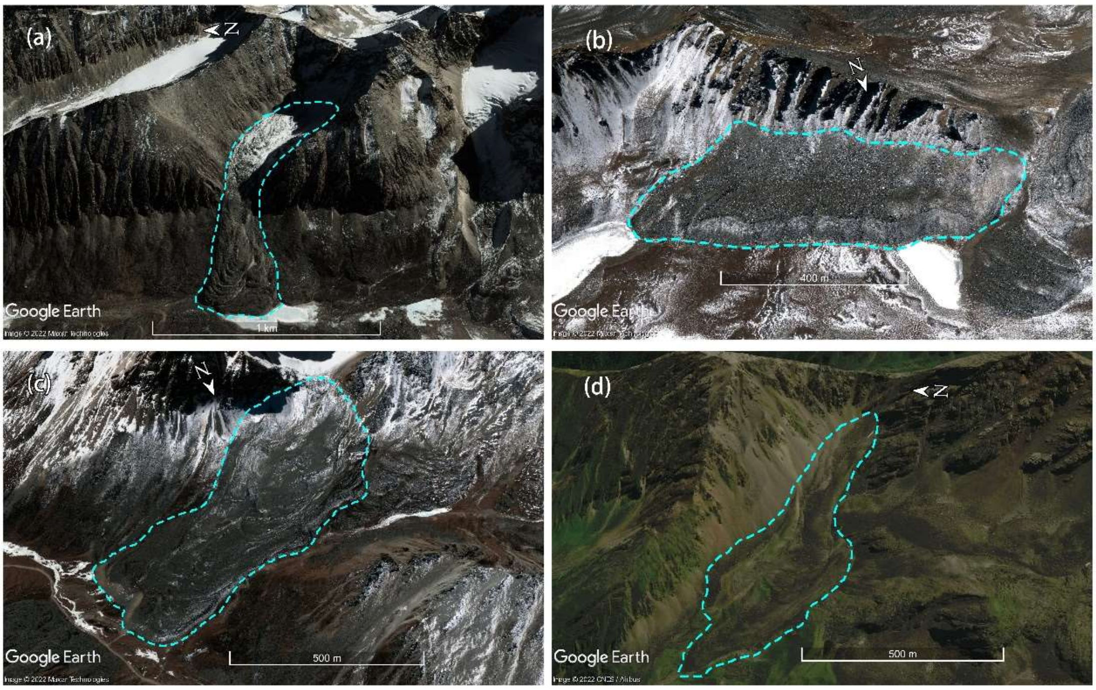


Figure 2: Example images of different types of rock glaciers in the GKLRJ. (a) An intact debris-derived rock glacier; (b) an intact talus-derived rock glacier; (c) a relict debris-derived rock glacier; (d) a relict talus-derived rock glacier. Images from ©Google Earth.

All shapefiles were fed into~~in~~ the 1984 UTM Zone 46N projection system to extract their~~the~~ topographic attributes using~~in~~ ArcGIS 10.7 software. The parameters (*i.e.*, latitude, longitude, area, length and~~,~~ width) of each rock glacier were calculated directly in ArcGIS to further divide the geometric~~geometry~~ types according to their~~the~~ length-width ratios. Rock glaciers with a length/width ratio of < ~~<~~1 were~~are~~ classified as lobate-shaped rock glaciers, while those with a length/width ratio of > ~~>~~1 were~~are~~ classified as tongue-shaped rock glaciers (Baroni *et al.*, 2004; Nyenhuis *et al.*, 2005; Scotti *et al.*, 2013). Topographic data were derived from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 3 (ASTER GDEM v3~~V3~~). We measured the mean altitude of each rock glacier, and quantified the slope and aspect of each rock glacier using the Surface tools in the ArcGIS Spatial Analyst toolbox. Each attribute was extracted using~~by~~ the ArcGIS Zonal Statistics tool.

~~To further reduce the subjectivity associated with the identification, digitization, and classification of landforms introduced by factors such as cloud cover, snowfall coverage, and image quality in the inventory, we assessed the uncertainty for each rock glacier according to the method provided by Schmid *et al.* (2015), which have been widely used in the previous studies (Jones *et al.*, 2018b; Brardinoni *et al.*, 2019)(see Table.2). Most of the assessment work was finished in Google Earth Pro, and we rechecked the remote sensing image in Mapcarta (https://mapcarta.com/Map) when the rock glacier was covered by snow and without other period images. Finally, we recorded the certainty index of each rock glacier in the attribute table (see Supplementary).~~

Table 2: Certainty Index applied to each rock glacier (Jones *et al.*, 2018b)

Parameter	Parameter options (index code)		
	1 point	2 points	3 points
External boundary	None (ON)	Vague (OV)	Clear (OC)
Snow coverage	Snow (SS)	Partial (SP)	None (SN)
Longitudinal flow structure	None (LN)	Vague (LV)	Clear (LC)
Transverse flow structure	None (TN)	Vague (TV)	Clear (TC)
Front slope	Unclear (FU)	Gentle (FG)	Steep (FS)
Certainty Index score	Medium certainty (MC) ⩽5	High certainty (HC) 6 to 10	Virtual certainty (VC) ⩾11

To reduce further the subjectivity associated with the identification, digitization and classification of landforms introduced by factors such as cloud cover, snowfall coverage and image quality in the inventory, we assessed the uncertainty for each rock glacier according to the method provided by Schmid *et al.* (2015), which has been widely used in previous studies (Jones *et al.*, 2018b; Brardinoni *et al.*, 2019; see Table 2). Most of the assessment work was finished in Google Earth Pro, and we rechecked the remote sensing image in Mapcarta (https://mapcarta.com/Map) when the rock glacier was covered by snow, and without other period imagery. Finally, we recorded the certainty index of each rock glacier in the attribute table (see Supplementary Materials).

3.2 Estimating hydrological stores

To ~~better~~ calculate more accurately the water content (water volume equivalent, WVEQ [km^3]) of intact rock glaciers and clean ice glaciers in the GKLRJ (Jones *et al.*, 2018b), we chose two different methods derived from Brenning *et al.* (2005a) and Cicoira *et al.* (2020).

The method for calculating the ice volumes of rock glaciers provided by Brenning *et al.* (2005a) requires~~required~~ multiplying the mean thickness, surface area~~,~~ and ice content of each rock glacier as in~~the~~ Eq.

(1), then converting them to the WVEQ by assuming anthe ice density conversion factor of 0.9 g cm^{-3} (≡900 kg m^{-3}) (Paterson, 1994; Jones *et al.*, 2018b), thus:).

$$V_{RG} = \text{Area} * \text{Mean thickness} * \text{Ice Content} \quad \_, \tag{1}$$

Based on field data from Brenning *et al.* (2005a) and a rule-of-thumb given by Barsch (1977c) for the Swiss Alps, the rock glacier thickness was modeled empirically as Eq. (2), thus:).

$$\text{Mean thickness [m]} = 50 * (\text{Area [km}^2])^{0.2} \quad \_, \tag{2}$$

The method provided by Cicoira *et al.* (2020),) based on the analysis of a dataset of 28 rock glaciers from the Alps (23) and the Andes (5), estimated the thickness of the rock glacier thickness usingwith a perfectly plastic model arrived at by solving Eq.Equation (4) for *H*, assuming a yield stress of *τ* = 92 kPa (takinggiven the mean driving stress from the dataset as a given), thus:):

$$H = \frac{\tau}{\rho\ g\ sin\alpha} \pm 3.4m \tag{3}$$

where τ is the sheer stress (τ= 92 kPa), *g* is the gravitational acceleration, *H* is the thickness of the moving rock glacier, *α* is the angle of the surface slope angle and *ρ* is the density of the creeping material, which is given by the contribution of volumetric debris w_d and ice content w_i and the relative densities (ρ_i = 910 kg m^{-3} and ρ_d = 2700 km m^{-3}), thus:):

$$\rho = \rho_d\, w_d + \rho_i\, w_i \tag{4}$$

Rock glaciers do not contain 100% ice by definition, and the ice content within them is spatially heterogeneous. We thereforeTherefore, we used globalthe worldwide estimates offor ice content within rock glacier ranges to further calculate their lower (40%), mean (50%)%), and upper (60%) ice volumesvolume (Hausmann *et al.*, 2012; Krainer and Ribis, 2012; Rangecroft *et al.*, 2015; Jones *et al.*, 2018b; Wagner *et al.*, 2021). In this studycase, the results of the calculations that used acalculation at 50% ice content werewill be used for subsequent comparisons with clean ice glaciers.

The iceIce volume of clean ice glacier was calculated usingfrom the following Eq. (5), thus:):

$$V = A * H\ \ , \tag{5}$$

where *V* represents ice volume, *A* is the glacier surface area derived from the second Chinese glacier inventory dataset of China (version 1.0) (2006-2011) (Liu *et al.*, 2012), and *H* is the ice thicknessthicknesses calculated usingby the GlabTop2 in Python 3.10 (Linsbauer *et al.*, 2009). We assumed a 100% ice content by volume and applied the above ice density conversion factor to calculate the water equivalent volume of clean ice glaciers.

To mitigate the additional impact caused by the uneven spatial distribution of glaciers and rock glaciers in the GKLRJ, we calculated a ratio of intact rock glaciers' to clean ice glaciers' water volume equivalence (WVEQ) by using the weighted average method that employsfrom the following equation:.

$$\text{WVEQ ratio}_{\text{Rg: Glacier}} = \frac{\text{WVEQ R1}_{\text{Rg}} \times \frac{\text{R1}_{\text{Rg}}}{\text{All}_{\text{Rg}}} + \text{WVEQ R2}_{\text{Rg}} \times \frac{\text{R2}_{\text{Rg}}}{\text{All}_{\text{Rg}}} + \text{WVEQ R3}_{\text{Rg}} \times \frac{\text{R3}_{\text{Rg}}}{\text{All}_{\text{Rg}}}}{\text{WVEQ R1}_{\text{Glacier}} \times \frac{\text{R1}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}} + \text{WVE R2}_{\text{Glacier}} \times \frac{\text{R2}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}} + \text{WVE R3}_{\text{Glacier}} \times \frac{\text{R3}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}}} \quad (-(6)) -$$

where WVEQ ratio$_{\text{Rg: Glacier}}$ is the ratio of intact rock glaciers' to clean ice glaciers' WEVQ; WVEQ Rn$_{\text{Rg}}$ (n = =1, 2, 3) respectively are the WVEQ values for rock glaciers in R1, R2 and R3, respectively; Rn$_{\text{Rg}}$ (n = =1, 2, 3) respectively are the numbersnumber of rock glaciers in R1, R2 and R3, respectively; All$_{\text{Rg}}$ is the number of rock glaciers in the whole GKLRJ; WVEQ Rn$_{\text{Glacier}}$ (n = =1, 2, 3) respectively are the WVEQ values for clean ice glaciers in R1, R2 and R3, respectively; Rn$_{\text{Glacier}}$ (n = =1, 2, 3) respectively are the number of clean ice glaciers in R1, R2 and R3, respectively; and; All$_{\text{Glacier}}$ is the number of clean ice glaciers in the whole GKLRJ.

3.3 Permafrost probability distribution

The binary logistic regression model has been used in several studies worldwide ~~appropriate~~ to calculate permafrost~~the~~ probability ~~of permafrost~~ distribution ~~in several studies worldwide~~ (Sattler *et al.*, 2016; Deluigi *et al.*, 2017; Baral *et al.*, 2019; Hassan *et al.*, 2021). A logistic regression model can be formulated as Eq. (7), thus:~~):~~

$$P(\mathrm{Y}=1)=\frac{1}{1+e^{-(\beta_0+\Sigma\beta_n X_n)}} \quad (7)$$

where $P(\mathrm{Y}=1)$ is the probability of outcome Y taking the value 1, β_0 is the intercept, and β_n is the regression coefficient of the independent variable X_n and is considered a predictor for the outcome Y. e is the base of the natural logarithm (Hassan *et al.*, 2021).

As viscous creep features in perennially frozen rock-ice mixtures, intact rock glaciers are considered to be direct expressions of permafrost. After calibrating the rock glacier~~Use was made for corresponding model development and calibration of their~~ inventory for the GKLRJ~~classified~~ by taking activity state~~status~~ as the dependent variable, its~~the~~ intact and relict rock glaciers were taken to represent~~respectively represented~~ the occurrence (1) and non-~~not~~ occurrence (0) of permafrost, respectively~~.~~. The spatially distributed local topo-climatic data (see Table 3)~~,~~, *i.e.*, longitude, latitude, mean altitude (ASTER GDEM v3), ~~V3), mean annual precipitation (~~MAP~~)~~ in 2015 (Du and Yi, 2019), ~~mean annual ground temperature (~~MAGT~~)~~ in 2015 (Du and Yi, 2019), mean slope and area (calculated in ArcGIS 10.7 based on ASTER GDEM v3~~V3~~) were used as the independent variables. All datasets were resampled to the same spatial resolution with the altitude~~elevation~~ data (~ 30 m) using~~by~~ the Nearest Neighbor method in ArcGIS 10.7 prior to~~before the~~ analysis.

Table 3: Topo-climatic data information.

Factor	Year	Data source	Resolution
Latitude	/	Google Earth Pro	/
Longitude	/	Google Earth Pro	/
Area	/	ArcGIS 10.7	/
Mean altitude	2000-2013	ASTER GDEM v3~~V3~~	30 m
Slope	2000-2013	ASTER GDEM v3~~V3~~	30 m
MAGT	2005-2015	Ran *et al.*, 2019	1 km
MAP	2015	Du and Yi, 2019	1 km

MAGT: mean annual ground temperature
MAP: mean annual precipitation

We used the Forward Selection (Likelihood Ratio) method in SPSS 27.0 to stepwise select the topo-climatic variables for building the logistic regression model. The performance of the model was measured by calculating the area under the receiver operating characteristic (AUROC). A model providing excellent prediction has an AUROC higher than 0.9, a fair model has an AUROC between 0.7 and 0.9, and a model is considered poor if it has an AUROC lower than 0.7 (Swets, 1988, Marmion *et al.*, 2009).

4 Results

4.1 Rock glacier inventory

4.1.1 Rock glacier~~glaciers~~ types and their distribution

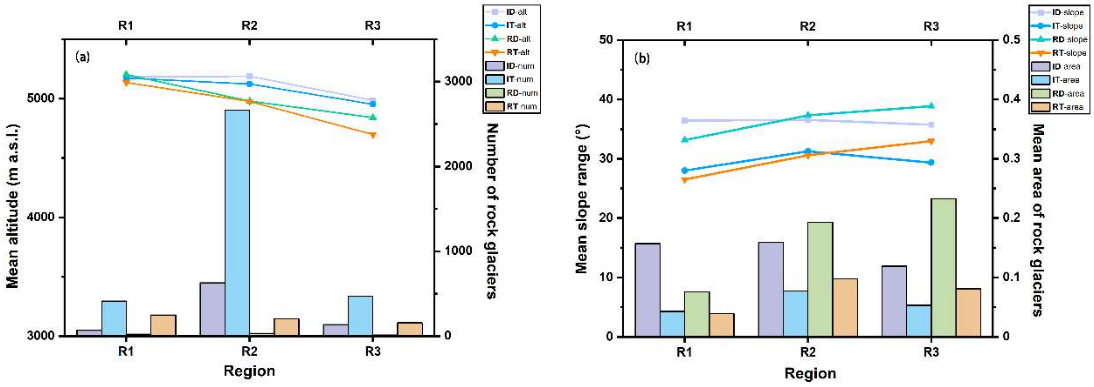
~~**Table 4: Mean characteristics for rock glaciers.**~~

~~Type~~	~~R1~~	~~R2~~	~~R3~~

~~Number~~	~~750~~	~~3529~~	~~774~~
~~Mean altitude (m a.s.l.)~~	~~5163~~	~~5125~~	~~4905~~
~~Mean MEF (m a.s.l.)~~	~~5116~~	~~5060~~	~~4845~~
~~Mean area (km^3)~~	~~0.05~~	~~0.09~~	~~0.07~~
~~Mean slope range (°)~~	~~28.42~~	~~32.21~~	~~31.36~~
~~Mean MAGT (℃)~~	~~-0.66~~	~~-0.60~~	~~-0.96~~
~~Mean MAAT (℃)~~	~~-1.67~~	~~-1.96~~	~~-1.72~~
~~Mean MAP (mm)~~	~~339~~	~~390~~	~~502~~

~~MEF: minimum elevation at the front~~
~~MAGT: mean annual ground temperature~~
~~MAAT: mean annual air temperature~~
~~MAP: mean annual precipitation~~

We identified a total of 5,053~~5053~~ rock glaciers in the GKLRJ, including 830 intact debris rock glaciers (16%), 3,548~~3548~~ intact talus rock glaciers (70%), 68 relict debris rock glaciers (1%) and 607 relict talus rock glaciers (12%). ~~~About ~~~46% of the rock glaciers were classified as lobate-shaped, and ~ 54%~~the rest of the rock glaciers classified~~ as tongue-shaped. Talus~~ accounted for ~54%. Regionally, the talus~~-derived rock glaciers are~~were~~ predominant in each region (Fig. 3a).~~3(a)).~~ However, rock glaciers are~~were~~ unevenly distributed in R1, R2 and~~,~~ R3, with nearly 70% of rock glaciers (n = 3,529~~3529~~) distributed in R2 (see Table ~~.~~4).



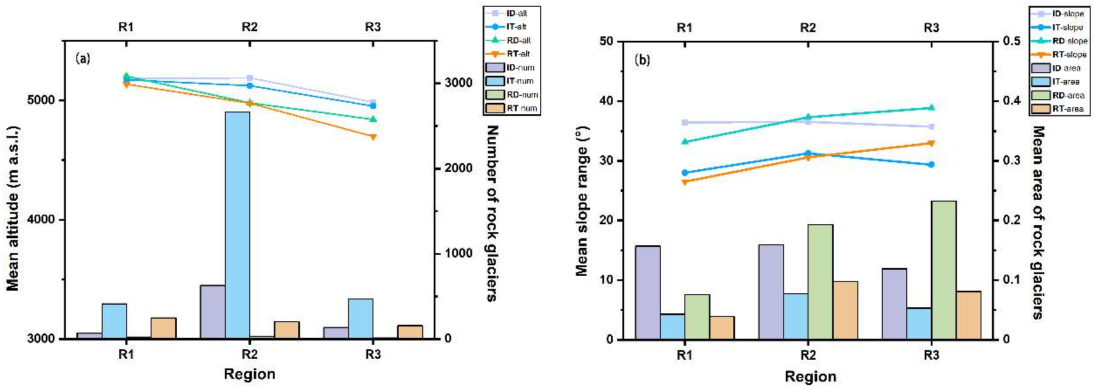
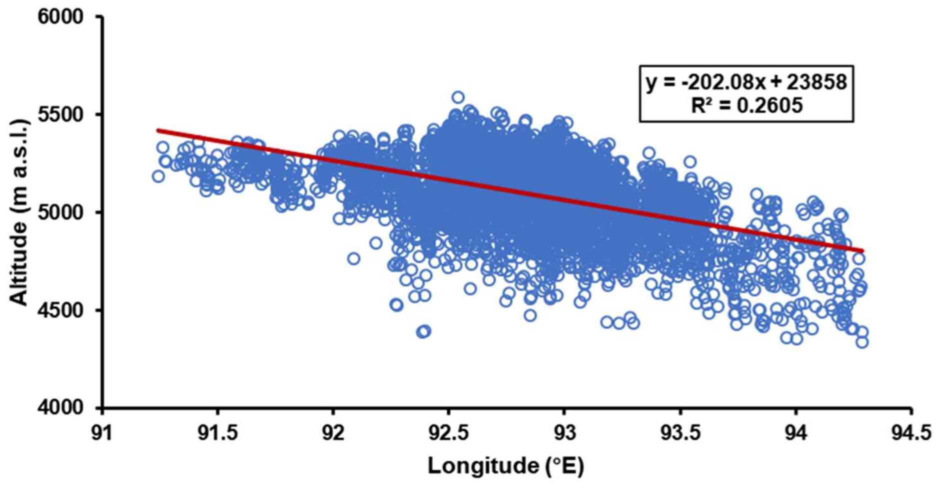


Figure 3: (a) Mean altitude and numbers of rock glaciers, by type;~~number,~~ (b) mean ~~slope~~ range of slope and mean area of intact debris rock glaciers (ID), intact talus rock glaciers (IT), relict debris rock glaciers (RD) and relict talus rock glaciers (RT) in R1, R2 and R3.



~~Figure 4: Scatter plots and fitted curves of the mean distribution altitude of rock glaciers versus longitude.~~

~~The mean altitude of rock glaciers distribution showed that about of~~ 90% of the rock glaciers are located between 4,800~~4800~~ and 5,400~~5400~~ m asl,~~a.s.l.,~~ with a mean~~an average~~ altitude of ~ 5,123~~about 5123~~ m asl~~a.s.l~~. Intact rock glaciers are~~were~~ statistically distributed at~~in a~~ higher altitudes~~altitude~~ than relict rock glaciers (ANOVA: *F*-value = 334.711, df within groups = 1, between groups = 5051, $p \leq$ ~~≤~~0.001), at ~ ~~which about~~ 140 m higher.~~ on the whole.~~ The mean altitude of rock glaciers ~~distributed~~ in R1 (5,203~~(5203~~ m asl) is~~a.s.l,) was~~ higher than for those~~that~~ in R2 (5,189~~(5189~~ m asl)~~a.s.l.)~~ and R3 (4,987~~(4987~~ m asl) by ~ ~~a.s.l.) about~~ 40 m and ~ 250 m, respectively (see Table ~~.~~4). The~~And the result showed that the~~ lower altitudinal limit ~~altitude~~ of rock glaciers declines~~distribution declined~~ as ~~the~~ longitude increases eastward~~increased~~ (see Fig. 4).

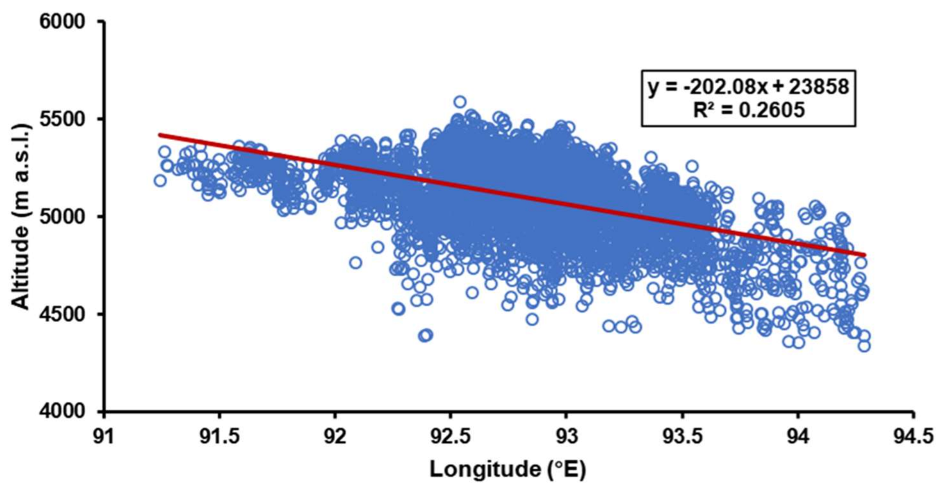


Figure 4: Scatterplots and fitted curves of the mean altitudinal distribution of rock glaciers *versus* longitude.

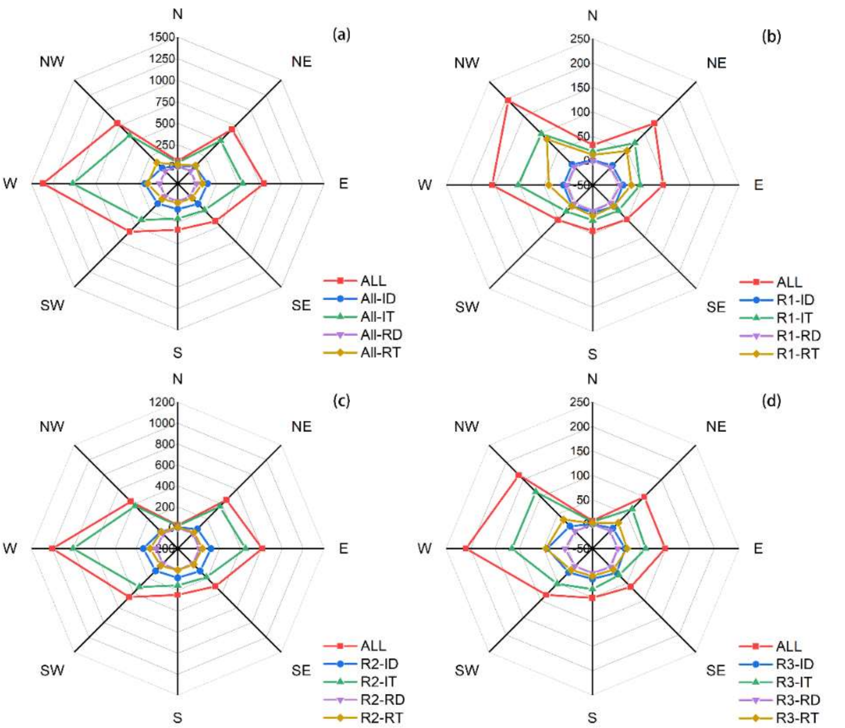
In the GKLRJ, rock glaciers cover~~covered~~ an area of 428.71 km^2, with the mean area of each rock glacier being 0.08 km^2. The different types of rock glaciers vary~~varied~~ considerably within~~ the~~ mean area (ANOVA: *F*-value = ~~=~~215.769, df within groups = 3, between groups = 5049, $p \leq$ ~~≤~~0.001). Debris-derived rock glaciers (0.15 km^2) generally have~~had~~ a larger~~large~~ mean area than the talus-derived ones (0.07 km^2), and ~~the~~ relict debris rock glaciers have~~glacier had~~ a larger mean area (0.16 km^2) than the other types. The~~ on the whole. In R2, the~~ mean area of most types of rock glacier is~~glaciers was~~ the highest in R2, except for~~the~~ relict debris rock glaciers, where it is~~ was~~ smaller than in R3 (Fig. 3).

Table 4: Mean characteristics for rock glaciers.

Type	R1	R2	R3
Number	750	3,529	774
Mean altitude (m asl)	5,163	5,125	4,905
Mean MEF (m asl)	5,116	5,060	4,845
Mean area (km^3)	0.05	0.09	0.07
Mean slope range (º)	28.42	32.21	31.36
Mean MAGT (ºC)	-0.66	-0.60	-0.96
Mean MAAT (ºC)	-1.67	-1.96	-1.72
Mean MAP (mm)	339	390	502

MEF: minimum altitude at the glacier front
MAGT: mean annual ground temperature
MAAT: mean annual air temperature
MAP: mean annual precipitation

The mean slope range of surface slope of rock glaciers in the GKLRJ is ~was about 30.46º;46° , while this value isextent was larger than forin R1 (28.42º42°), but smaller than forin R2 (32.21º21°) and R3 (31.36º) (36°)(see Table .4). Moreover, the debris-derived rock glaciers generally greater ranges inhad the larger slope range than the talus-derived rock glaciers. The mean , and the slope range of slope of the relict debris rock glaciers in R3 is the largest (38.87º) (87°)(Fig. 3).



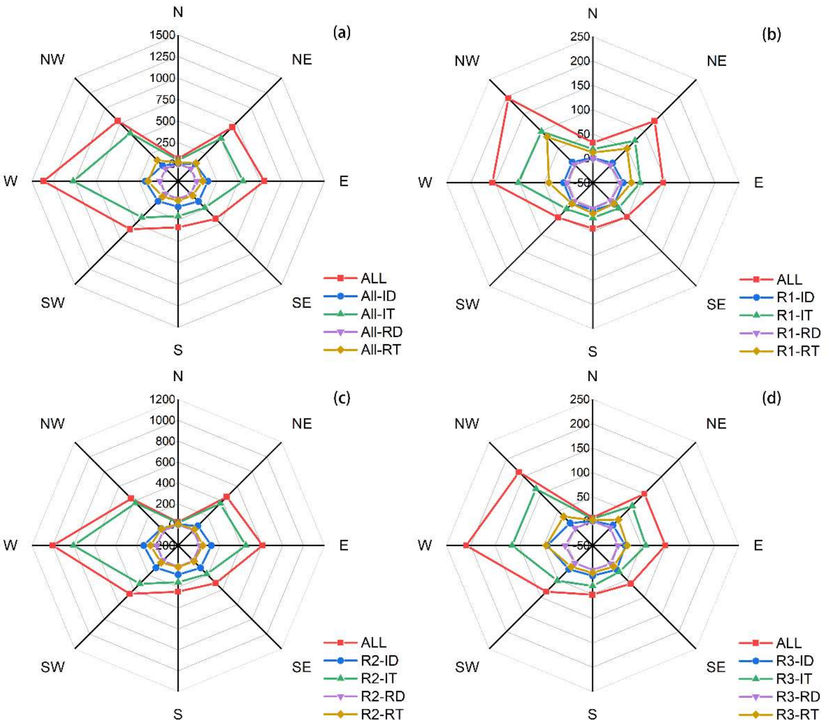


Figure 5: Analysis of abundances for different rock glacier activity states. of rock glaciers. The numbersnumber of rock glaciers for each aspect on the four radar plots areis shown as percentagesa percentage (%). Note: ID =is the intact debris-derived rock glacier;, IT =is the intact talus-derived rock glacier;, RD =is the relict debris-derived rock glacier;, and RT =is the relict talus-derived rock glacier.

Rock glaciers predominantly occuroccurred on the west-facing slopesaspect (W, 26.97%; NW, 15.69%; SW, 11.68%), with some distributed on the east-facing aspectsaspect (E, 15.85%; NE, 13.62%), and fewestleast distributed on north-facing slopes (1.23%) aspect (see Fig. 5). This is because of the existence offeature was mainly determined by the numerous talus rock glaciers. The numbersRegionally, the characteristic of rock glaciers distributed on each aspect are consistent with those forthat in the whole study area, althoughwhile the distribution proportion of rock glaciers distributed on west-facing slopesthe W aspect in R1 and R3 iswas larger than that in R2.

4.1.2 Validation of the rock glacier inventory

Nearly 90% of rock glaciers in the GKLRJ havehad uncertainty indicesindexes concentrated between 9 and 12. Of these, the same number of rock glaciers with uncertainty 10 and 11 (n = 1,507)=1507), account for nearly 60% of the total rock glaciers. In general, the number of rock glaciers. In general, the numbers of rock glaciers classified as 'high'High certainty' (n = 2,495=2495) and 'virtual'Virtual certainty' (n = 2,558) are similar=2558) were close to each other, with a relatively even spatial distribution. Intact rock glaciers generally havehad a high certainty index, with all of them being 'virtual'Virtual certainty'. Regionally, the main factors contributing to increased uncertainty vary between regions. The rock glaciers in R1 tendtended to be less clear in terms of theirthe flow structure, while those in R2 and R3 arewere mainly influenced by the snow coverage. FurthermoreAlso, the collapsedcollapse structures of the relict rock glaciers in R3 makemade their surfacessurface much more subdued than those ofon intact rock glaciers.

4.2 Water equivalent volumes

Based on the second Chinese glacier inventoryglacial catalogue data set of China (Liu *et al*., 2012), clean ice glaciers in the GKLRJ covercovered an area of ~about 372.32 km^2. GlabTop2 provided estimated clean ice glacier thicknesses ranging between ~ 1 and ~ 263 m (mean = ~ 18 m). WeFinally, we estimated the total WVEQ of the region's clean ice glaciers to be ~ 9.29 km^3.

Table 5: Ice volumesvolume (km^3) and corresponding WVEQsWVEQ (km^3) calculated usingby the empirical area-thickness formula (Brenning, 2005a) forin sub-regions and GKLRJ-wide (All).

Brenning, 2005a					
Region	Glacier - WVEQ (km^3)	RG - WVEQ (km^3)			RG: Glacier WVEQ ratio
		40%	50%	60%	
All	9.29	4.55	5.69	6.82	1:1.81
1	0.19	0.34	0.43	0.51	2.26:1
2	6.60	3.73	4.66	5.59	1:1.42
3	2.51	0.48	0.60	0.72	1:4.18

WVEQ = water volume equivalent.

The mean ice thickness of intact rock glaciers in the GKLRJ estimated usingby the empirical area-thickness formula (Brenning, 2005a) is ~was about 28.48 m. The WVEQ storage lieswas between 4.55 and 6.82 km^3, ofamong which R2 stores ~stored about 80% of the water in the GKLRJ (*i.e.*, ~about 3.73-5.59 km^3).. R1 storesstored 0.34 - 0.51 km^3 of water (which accounts for 8% of the whole GKLRJ reserve).. And R3 stores ~stored about 11% of the water, or about 0.48 - 0.72 km^3(see Table .5). Compared to the WVEQ of clean ice glaciers, the result calculated usingby the weighted method showed that the ratio was 1:1.81, indicating that glaciers stored ~ 1.81 times more water volume than intact rock glaciers.

Table 6: Ice volumesvolume (km^3) and corresponding WVEQsWVEQ (km^3) calculated usingby the perfectly plastic model (Cicoira *et al.*, 2020) forin sub-regions and GKLRJ-wide (All).

Cicoira *et al.*, 2020					
Region	Glacier - WVEQ (km^3)	RG - WVEQ (km^3)			RG: Glacier WVEQ ratio
		40%	50%	60%	
All	9.29	1.93 – 2.85	2.71 – 3.86	3.69 – 5.07	1:3.20
1	0.19	0.16 - 0.23	0.22 - 0.31	0.30 - 0.41	1.42:1
2	6.60	1.54 – 2.29	2.16 – 3.09	2.94 – 4.06	1:2.51
3	2.51	0.24 - 0.34	0.34 - 0.46	0.45 - 0.61	1:6.28

WVEQ = water volume equivalent.
The range of results in RG - WVEQ (km^3) (Cicoira *et al.*, 2020) corresponds to the $H \pm 3.4$ m4m.

The mean thickness of rock glaciers calculated using aby the perfectly plastic model (Cicoira *et al.*, 2020) iswas 19.15±3.4 m, which was 9.33 m thinner than that estimated usingby the empirical area-thickness formula. The On the whole, the mean value of the WVEQ estimated usingby this method is ~was about 56-67% of the mean value obtained usingby the '"Brenning'" method. As the estimated WVEQ of rock glaciers decreases, the ratio of rock glaciers' to clean ice glaciers' WVEQ iswas also lower than that obtained usingof the 'Brenning'previous method (Brenning, 2005a)., indicating that the WVEQ of clean ice glaciers is ~was about 3.2 times that of rock glaciers (see Table .6).

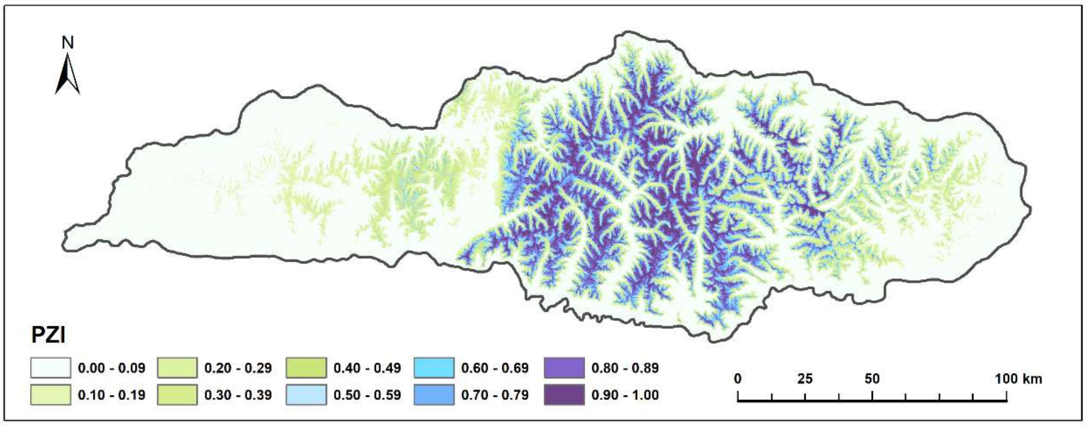
4.3 Logistic regression modelingmodelling of permafrost probability distribution

Table 7: Selection of dependent variables for the logistic modelLogistic regression output.

	B	SE	*p*	Exp(B)	BCa 95% CI(B)

					Lower	Upper
Mean altitude	0.007	0.000	0.000	1.008	1.007	1.008
Mean annual precipitation	-0.021	0.002	0.000	0.979	0.976	0.982
Mean slope	-0.041	0.009	0.000	0.960	0.943	0.977
Mean annual ground temperature	-0.145	0.073	0.047	0.865	0.750	0.998
Area	0.000	0.000	0.016	1.000	1.000	1.000
Longitude	4.327	0.215	0.000	75.742	49.659	115.524
Latitude	-2.320	0.275	0.000	0.098	0.057	0.168
Constant	-359.428	22.036	0.000	0.000		

WeBased on the output result, we generated the estimation model based the logistic regression analysis result, model that overall fit as well as all coefficient of variables included in the modelestimations were highly significant ($p < <$0.05, see Table .7). The Hosmer–Lemeshow test also showed thatmeant the model was a good fit (p = 0.709, p > 0.05). The area under the ROC curve (AUC) was calculated to be 0.85, which suggested thatappeared the model could be reliably used to predictfor the GKLRJ'sprobability prediction of permafrost probability distribution in GKLRJ.



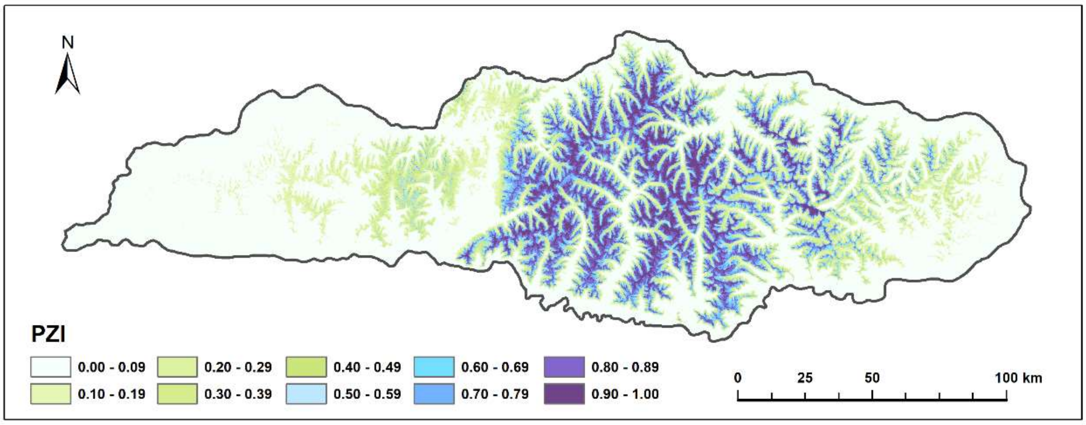


Figure 6: Permafrost probabilityProbability distribution map for the of permafrost in GKLRJ.

Based on the above model, we drew athe permafrost probability distribution map (Fig. 6). This map The result showed that ~approximately 30% of the GKLRJ (5,6515651 km^2) isare in the PZI ≥ 0.5 permafrost probability zone of PZI≥0.5. The maximum area (11,70811708 km^2; 51%) of the PZI occursoccurred between the PZI values of 0.10 to 0.19, with athe minimum altitude of 2,8842884 m asl,a.s.l., and close to the areas whererange of MAGT = 0.5ºC5 ℃ and MAAT = 0ºC0 ℃. The minimum altitude of permafrost probability areasarea with PZI valuesvalue in the range of 0.50 ~ 0.59 is 4,4764476 m asl, wherea.s.l., with the mean MAGT is ~ 0ºC, approximately 0℃ and close to the line of MAAT= -1ºC isotherm1℃. The minimum altitude of permafrost probability areasarea with PZI valuesvalue in the range of 0.89 ~ 0.99 is 4,790 ~ 5,8604790 ~ 5860 m asl, wherea.s.l., with the mean MAGT is ~about -1.5ºC5℃ and the mean MAAT is ~ -3ºCwas about -3℃, covering an area of 1,5211521 km^2 (6.6% of the total GKLRJ). As%). Because the minimum altitude of the PZI ≥ ≥0.5 areas iswas closest to the lower altitudinal limit altitude of rock glaciers distributed in the GKLRJ (~ 4,5004500 m asl),a.s.l.), so we chose 0.5 as the critical value to classify the presence of permafrost in the GKLRJ. PZI ≥ ≥0.5 indicates thatthe permafrost occurrence is probable, while PZI < 0.5 indicates thatthe permafrost occurrence is improbable., which means the possible presence of the primarily seasonal frost.

5 Discussion

5.1 Factors controllingControlling factors on rock glaciers

Rock glaciers are distributed heterogeneously throughout the GKRLJ, with most concentrated within R2. The GKLRJ spans a large area from east to west, with variations in topography and climatic conditions between the three sub-regions, thereby providingwhich provide the basis for a spatially differentiated distribution of rock glaciers. The development of rock glaciers is a complex function of responses to air temperature, insolation, wind and seasonal precipitation over a considerable time period (Humlum, 1998), with the altitude of MAAT = -2°C isotherm and the equilibrium line altitude (ELA) for localon glaciers (ELA) respectively forming the lower and upper boundaries of the cryogenic belt where they have developed, respectively –(Humlum, 1988; Brenning, 2005a; Rangecroft *et al*., 2015, 2016; Jones, 2018b). Topographically, the overall higher terrain in R2 has accommodatedcan accommodate the development of more rock glaciers in the area above 4,5004500 m asl.a.s.l. Meanwhile, R2 is located in the transition zone between the TP's semi-arid and sub-humid regions, with a meanan average ELA height of ~ 5,462about 5462 m asla.s.l. Compared with R3, which has a (Mean ELA = 5292 m a.s.l.) with lower ELA (mean ELA = 5,292 m asl), and R1, which has a with higher MAAT, R2 provideshas a large ecological niche for rock glacierglaciers development. AdditionallyIn addition, the widespread glacial remains in R2 and the predominance of more easily weathered granite as bedrock in this area could also provide a richer source of material for rock glacier development (Wahrhaftig and Cox, 1959; Haeberli *et al*., 2006).

The mean and lower altitudinal limitslimit altitude of the rock glacier distribution of rock glaciers in the GKLRJ decreasedecreases with increasing longitude from west to east, from 5,2005200 m asla.s.l. to ~ 4,900about 4900 m asla.s.l. In the Gangdise Mountains, located in the same latitudinal range on the western side of the study area, rock glaciers show a similar trend of gradually decreasing altitude in line with distribution height under conditions of increased moisture; indeed,, and the characteristics of the changes in the two regions show an overall continuity on the whole (Zhang *et al*., 2022). Limited by the range of the ISM, MAPsummer monsoon, the annual precipitation gradually decreasesdecreased from west to east from the Gangdise Mountains to the GKLRJ. In the alpine tundra of this region, annual precipitation is dominated by snowfall in summer and autumn. Increases in, and the increase of snowfall in summer and autumn could help to preserve permafrost, allowing permafrost to develop at lower altitudes under similarother same climatic conditions (Zhou *et al.,* 2000). Additionally, In addition, the annual regional precipitation values may reflect reductionscan be used as a reflection of the reduction in short-wave insolation arising fromdue to cloud cover, at least to some extent (Boeckli *et al*., 2012a).

RelativelyIn the range of meeting the development conditions of rock glaciers, relatively favorable hydrologicalwater conditions will be more conducive to freeze-thaw weathering, thereby increasingand then increase the generation rate of rock debris, which in turn is conducive to the development of rock glaciers (Hallet *et al*., 1991; Haeberli *et al*., 2006; Zhang *et al*., 2022). Increases in MAP are therefore likely to beTherefore, the increase of annual precipitation is conducive to the expansion of the rock glacier distribution range in the distribution of rock glaciers in semi-arid to sub-humid areas, meaning thatarea, and the lower altitudinal limit altitude of rock glacier distribution decreases with increases inthe increase of annual precipitation.

In the study area, rock glaciers are distributed mostlymost along west-facing aspectsthe W aspect, followed by the NW-facing slopes. aspect. This differs from the pattern in most regions where rock glaciers tendprefer to be located on north-facingin the northern (NW-N-NE) mid-latitude mountains where solar radiation input is low, all such as in the Himalayas (Jones *et al*., 2018b), Gangdise MountainsGangdises (Zhang *et al*., 2022), Tianshan Mountains (Liu *et al.*, 1995; Bolch and Marchenko, 2009) and the European Alps (Scotti *et al*., 2013). However, regional topographic conditions appear to), which all have a greater influence on the distribution of rock glaciers than an east-west trend and the solar radiation in the GKLRJ. The slopes herenorthern part of these mountains is significantly lower than in the other aspects. However, the mountains in GKLRJ are mainly in north-south trend and the slopes are predominantly east- and west--facing aspectsslopes, with the north--facing aspectsslope being lesson commonsmaller in the region,area and therefore unable to provide sufficient space for the distribution of rock glaciers. Therefore, rock glaciers within the GKLRJ are more commonly distributed on west-facing slopes, where the potential incoming solar radiation (PISR) calculated in SAGA 8.1.3 software is lower than forthe east-facing slopes.

RelictThe relict debris-derived rock glaciers exhibithave a greater variation in slope within R2 and R3 compared to other types of rock glaciers. This is probably because that R2 and R3 experiencehave more intense freeze-thaw processes and more widespread glacial relics compared with R1, potentially providingwhich could provide a richer source of debris for rock glacier development. TheseAnd the debris-derived rock glaciers tend to be predominantly tongue-shaped (83%), with greater mobility and slope variation than talus-derived rock glaciers. Moreover, relict rock glaciers tend to be longer (681 m) compared to intact rock glaciers (616 m), anotherwhich is also the important factor in making their slopes more variable.

5.2 Hydrological significanceSignificance of rock glaciers

In comparison, weit is found that the thicknesses of rock glaciers calculated usingbased on the flow plasticity model (Cicoira *et al*., 2020) are significantly lower than the corresponding results calculated usingby the empirical area-thickness formula (Brenning, 2005a), potentiallywhich may be due to the following three main reasons. Firstly, the slope angle of slope used to calculate the thickness may have been overestimated. Due to the lack of actual measurement data, we calculated the length of each rock glacier in ArcGIS based on the digitizeddigitization results, extracted its altitudinalelevation difference usingbased on DEM data, and finally applied trigonometric functions to calculate eachtheir slope angle of slope. Secondly, the slope angles of slope of some rock glaciers are outside the applicable slope range of this model (10°-30°). Since tongue-shaped rock glaciers on steep hillslopes tend to have steepergreater slopes and greater driving stresses, our estimates of thickness using the meanaverage parameters in the model may be lower. Thirdly, the applicability of different estimation methods may be different across the study area. The meanaverage thickness of rock glaciers in the study made by~~of~~ Brenning (2005a) is ~~~about~~ 10 m higher than the sample of rock glaciers selected in the study conducted by~~of~~ Cicoira *et al.* (2020). The thicknesses~~Therefore, the thickness~~ of rock glaciers estimated using Brenning's~~Brenning's~~ method may therefore be overestimates~~somewhat overestimated~~.

In order to facilitate comparison with the results of different studies worldwide, we chose to use the results obtained using~~through~~ the empirical area-thickness formula (Brenning, 2005a) for further discussion. These~~The~~ estimates indicate that the amount of water stored in rock glaciers in the GKLRJ is ~~~about~~ 5.5% of the total previously-~~-~~identified rock glacier water reserves globally (94.66 Gt),~~)~~ and ~~~about~~ 9% of the existing water reserves in rock glaciers on the TP~~Tibetan Plateau~~ (58.05 Gt) (Jones *et al.*, 2018a; Jones *et al.*, 2018b; Jones *et al.*, 2021). The rock glacier to glacier storage ratio in the GKJRJ of 1:1.82 is ~~~about~~ 340 times bigger than the global ratio (1:618, excluding the Antarctic and Subantarctic and Greenland Periphery Randolph Glacier Inventory) (Randolf Glacier Inventory (RGI);~~;~~ Pfeffer *et al.*, 2014; Jones *et al.*, 2018a), ~~~about~~ 14 times bigger than that of the Himalayas to its south (1:25) (Jones *et al.*, 2021), and much closer to that of the Andes in South America (1:3) (Azócar and Brenning, 2010),~~). These mainly because that the arid and semi-arid regions in the world~~ where glacier presence is also limited/absent~~ and presents spatial changes under different climatic and geomorphic environment conditions~~ (Schrott, 1996; Brenning, 2005b; Azócar~~Azocar~~ and Brenning, 2010; Millar and Westfall, 2019; Jones *et al*., 2019b; Schaffer *et al*., 2019). In the GKLRJ, regional~~Regionally,~~ differences in the hydrological significance of rock glaciers under different climatic conditions also exist (ANOVA: *F*-value =5 8~~58~~.263, df within groups = 1.773, between groups = 34.435, $p \leqslant$ ~~$\leqslant$~~0.001). In R2, which is located in the transition zone between the semi-arid and semi-humid zones, the higher topography and suitable hydrothermal conditions lead to the highest concentration of glaciers and rock glaciers in this area, with rock glaciers accounting for 82% ~~and glaciers accounting for approximately 73%~~ of the rock glacier water storage in the entire study area, and glaciers accounting for ~73% of the study area's glacial water storage, with a ratio of ~~~approximately~~ 1:1.42 between them. However, in terms of the ratio of rock glaciers to glacial water storage alone, rock glaciers are of greater hydrological significance in the warmer and drier R1, which has a storage capacity of only 7.6% of the total area. In the~~a~~ context of drought and climate warming, ~~the~~ rock glaciers store ~~even~~ more than twice the water of the glaciers in R1. This partly explains why rock glaciers have a~~show~~ greater hydrological significance and refuge potential as long-term reservoirs in arid regions with small and rapidly vanishing glaciers. Furthermore, the relationship between the proportion of the water cycle occupied by rock glaciers and the water requirements of regional populations should be considered in more detail. More~~And more~~ research is needed into~~on~~ the hydrochemical~~hydro-chemical~~ composition of the stored water in rock glaciers and whether it can be used for irrigation and drinking.

5.3 Rock glaciers can be used to model ~~the~~ permafrost probability distribution

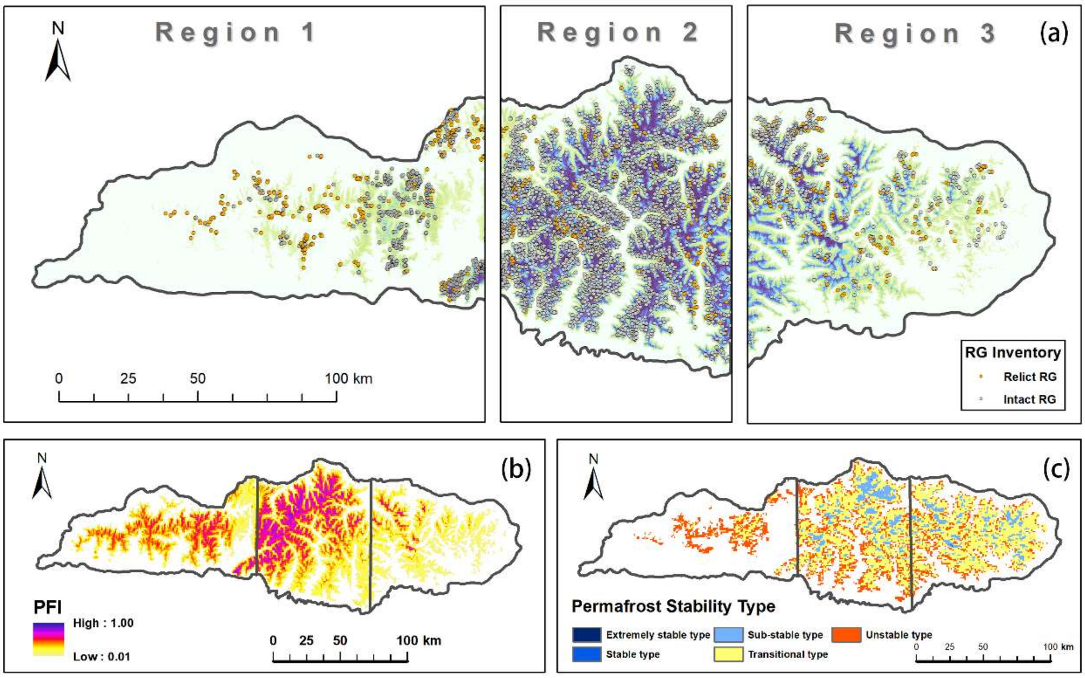


Figure 7: (a) Map of rock glaciers and permafrost probability distribution in the GKLRJ; (b) Gruber's (2012) Permafrost Zonation Index (PZI) for the GKLRJ; and (c) Map of the thermal stability of permafrost in the GKLRJ (Ran *et al.*, 2020).

The minimum altitude at the glacier front (MEF) of the intact rock glaciers (average = ~4,500~~4500~~ m asl)~~a.s.l.)~~ is close to the minimum altitude~~elevation~~ in the permafrost probability zone, with PZI > 0.50 (4,476~~4476~~ m asl)~~a.s.l.)~~, proving that the MEF of intact rock glaciers is a good indicator of permafrost distribution. Our ~~On the whole, our~~ predicted results~~result~~ are generally consistent with the ~~Zonation Index (~~PZI~~)~~ map (Gruber *et al.*, 2012; ~~)~~(Fig.7b)~~7(b))~~ and the thermal stability of permafrost (Ran *et al.*, 2020; ~~)~~(Fig.7c), confirming~~7(c)), which confirms~~ that our rock glacier~~-model~~-based model ~~on rock glaciers~~ has good applicability when~~in~~ simulating the distribution ~~range~~ of permafrost in the GKLRJ. When making detailed comparisons between~~In detail, by comparing~~ the mean MAAT data from 1961 to 1990 used in the study of Gruber *et al.* (2012) and MAAT data for~~of~~ the TP~~Tibetan Plateau~~ in 2015 provided by Du and Yi (2019), we found that, except for a few areas in the eastern~~east~~ part of R3, the mean MAATs~~MAAT~~ of R1 and R2 increased by ~ 2ºC~~about 2℃~~. Although there may have been~~be~~ some ~~data~~ errors in the data, the effect of temperature on the predicted permafrost distribution ~~,~~ for the model based on the relationship~~established according to the relationships~~ between air temperature and the occurrence of permafrost~~, the effect of temperature on the predicted results of permafrost~~ may nonetheless~~still~~ be somewhat magnified. These ~~Therefore, these~~ differences in ~~reference time period of~~ the climate data's reference time periods may have made~~cause that~~ our predicted range for R1significantly~~significantly~~ smaller than the range stated in~~from~~ Gruber *et al.* (2012)~~.) in R1.~~ In R3, the permafrost probability ~~of permafrost~~ distribution predicted by us is slightly lower than that of Ran *et al.* (2020), potentially~~which may be~~ related to the large number of relict rock glaciers in this area. Rock glaciers that extend so far from their source area, or into warmer climatic conditions at lower altitudes, may become inactive and evolve into relict rock glaciers. In these scenarios~~. In this case~~, the probability of permafrost occurrence in the region where the rock glaciers are located may be underestimated.

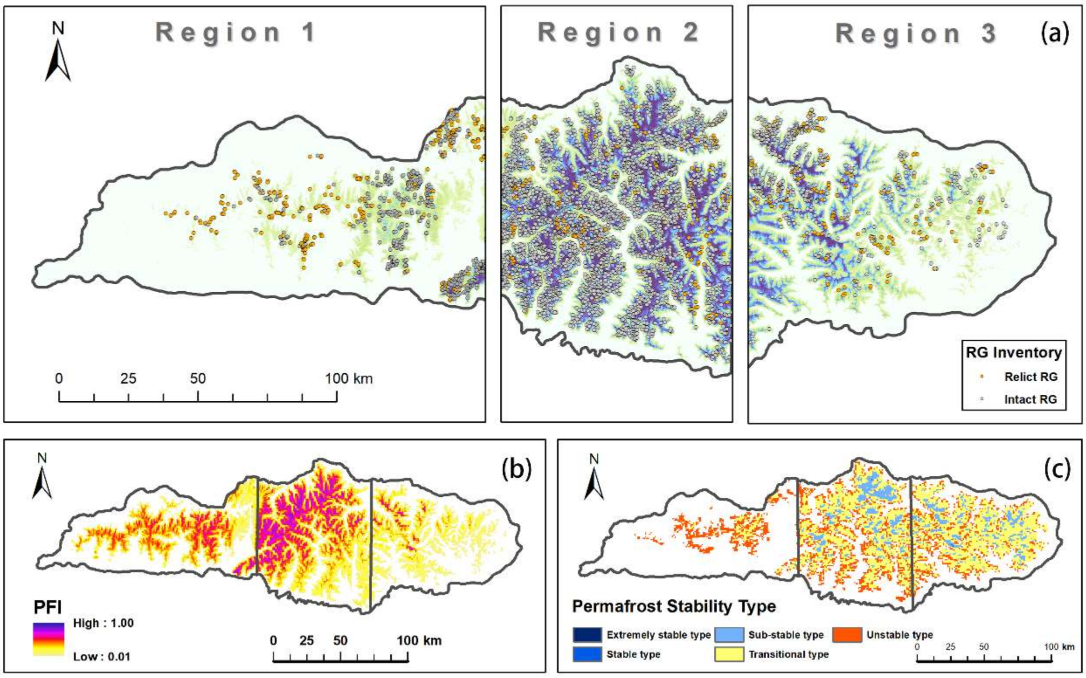


Figure 7: (a) Map of rock glaciers and permafrost probability distribution in GKLRJ, (b) Gruber's (2012) Permafrost Zonation Index (PZI) in GKLRJ, (c) Map of the thermal stability of permafrost in GKLRJ (Ran *et al.*,2020).

6 Conclusions

We constructed an inventory of rock glaciers in the GKLRJ and illustrated their regional distribution characteristics and environmental indications. We employedMeanwhile, we used two methods to estimate and compare the water storage capacity of the region'sof rock glaciers and mapestimated the GKLRJ's permafrost probability distribution usingby the logistic regression model. The results show that there are 5,053is a total of 5053 rock glaciers identified in the GKLRJ, covering an area of 428.71 km^2. Over 80% of these rock glaciers are located within R2, and that the high altitude (~ 4,9004900 m asl), low temperatures (MAAT ≤ -2ºC≤-2℃) and suitable precipitation (MAP ~(~ 400 mm) in the semi-arid and semi-humid transition zone provide the greatest ecological niche for rock glacier distribution in the regionarea. The lower altitudinalelevation limit of the distribution of rock glaciers decreases gradually with increasing longitude from the western side of the study area, from the Gangdise MountainsGanges to the interior of the GKLRJ, indicating the positive effect of increased precipitation on the preservation of permafrost. Based on the empirical area-thickness formula estimation result, we calculated that 4.55-6.82 km^3 of water is stored in the rock glaciers, or ~about 61% of the water glaciers presently store. The water volume estimated on the basis of the perfectly plastic model is 56-67% of this result. Despite thesethe differences, both of these results reveal the previously neglected and important hydrological value of rock glaciers in the GKLRJ, particularly in R1, which is the drier sub-region. The WVEQ in rock glaciers and the ratio of rock glaciers to clean ice glaciers may continue to increase with global warming and as glaciers retreat in the future. The estimated results of our regression model are in good agreement with the predictions obtained usingby other methods and are also consistent with the actual distribution of rock glaciers. The lower altitude of the PZI ≥ ≥0.5 regions (~ 4,5004500 m asl) matches the boundary of the rock glacier distribution and the MAGT=0ºC0℃ isotherm, indicating that permafrost probably occurs. This also demonstrates that our predictive approach using~~based on~~ the rock glacier inventory can~~could~~ better tackle the inherent interpretive problems caused by the region's complex topographic changes, as well as ~~and~~ reflect more accurately the GKLRJ's current permafrost probability ~~of permafrost~~ distribution.~~–~~

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Data availability. The data associated with this article can be found in the Supplementary Materials~~Supplement~~. These data include the Google maps of the most important areas described in this article, as well as a tabulation of the parameters of the rock glaciers~~,~~ found in the GKLRJ.

Author contributions. ML and GL designed the research. ML performed the analysis and wrote the paper. YY and ZP provided overall supervision and contributed to the writing.

Competing interests. The authors declare that they have no conflict of interest.

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